

Natural Gas Locomotives



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How to Carry LNG for the Locomotives

➤ Tender Cars

- Generally needed for road locomotives to carry sufficient LNG for long journeys, to minimize the number of fueling stations

➤ Belly tanks

- Preferred for switching locomotives which need lesser volumes of fuel

Engine Issues

Railroad locomotives have two different types of engines:

- **Four-stroke cycle engines**, manufactured by General Electric and Caterpillar
- **Two-stroke cycle engines**, manufactured by Electro Motive Diesel, now a division of Caterpillar

There are different approaches to having these two types of engines run on natural gas.

Engine Issues

(Continued)

Four principal types of natural gas-fueled diesel engines:

- Low-pressure (100 psig), early-cycle direct injection of NG into the cylinders, pilot injection of diesel fuel for ignition; 2-stroke cycle engines *
- Low-pressure (100 psig), early-cycle direct injection of NG into the cylinders, spark ignition; 4-stroke cycle engines
- Low-pressure (100 psig) injection of NG into the inlet air before it reaches the cylinder (“fumigation”); injection of diesel fuel for ignition; 4-stroke cycle engines *
- High-pressure (3000 psig), late-cycle direct injection of LNG into the cylinders, pilot injection of diesel fuel for ignition; 2 or 4-stroke cycle engines *

* These engines can also run on straight diesel fuel

Engine Issues

(Continued)

- To prevent pre-ignition of NG (“knocking”) in the cylinders, there are two alternative approaches:
 - Derate the engine by reducing the compression ratio – accomplished with new pistons and/or cylinder heads
 - Cool the inlet air into the cylinders
- Some NG engines are purposely derated so they can burn “pipeline gas” containing heavier hydrocarbons from the gas fields.
- Engines running on NG experience greatly reduced wear of valves and piston rings and liners, but need special lubricants; cuts consumption of repair parts.

Engine Issues

(Continued)

- Dual-fuel conversion kits include:
 - Natural gas injectors, either for gaseous NG or LNG
 - New cylinder heads to accommodate the injectors in two-stroke cycle engines
 - New pistons with an altered shape to provide better “swirl” for complete combustion
 - Electronic controller for the fuel injectors (EFI)
 - Modified coolant cycle piping and radiators
- Two-stroke cycle engines easier to convert than four-stroke cycle engines – they have more space around the cylinder heads for injector installation
- Spark-ignited engines are built new, not converted

Equipping Locomotives – Road Units vs. Switchers

- The more low-cost NG that a locomotive burns, rather than high-cost diesel fuel, the more attractive the use of natural gas becomes.
- Road locomotives consume a great amount of fuel, and the economic case for converting them to natural gas is strong.
- If utilization rates of road locomotives can be increased, it improves the economic case for converting them to natural gas.
- Switcher locomotives do not consume much fuel, so the economic case for running them on NG is not strong.
- NG switcher locomotives, though, can help meet strict air quality standards in urban areas.

Fueling Station Issues

- For demonstration programs, a fueling station needs storage tanks and pumps for trucked-in LNG.
- For large-scale programs, LNG liquefaction plants with storage tanks would be built where NG pipelines are in close proximity to rail lines.
- Such liquefaction/fueling stations are expensive and only a limited number would be built on high-density corridors (and not everywhere there is a diesel fueling station).

Fueling Station Issues

(continued)

- Tender cars loaded at fueling station get swapped out with empty tender cars on arriving trains; no waiting while tender cars are filled.
- Because railroaders have no knowledge of how to deal with NG and LNG, it is best to have fueling stations managed by firms that are in the business of handling gases and cryogenic liquids, e.g. Air Products & Chemicals, Air Liquide, BOC, Koch Industries, Linde, Shell.
- LNG is nearly pure methane; heavier hydrocarbons boil off during the liquefaction process.

NG Loco Demo Program

Burlington Northern Railroad 1988-1995



NG Loco Demo Program

Burlington Northern Railroad 1988-1995

(continued)

- Revenue service first on local trains on Olympic Peninsula, then on coal trains for four years (1991-1995) between Wyoming and northern Minnesota and Wisconsin
- Achieved full rated horsepower with an innovative heat transfer system: it moved warmed “coolant” from engine to tender car to vaporize the LNG so it could move to engine as a gas; the cooled “coolant” was then moved back to the engine aftercooler where it was used to cool the inlet air entering the cylinders.
- Was given AAR’s 1992 award for “Outstanding Technical Achievement”
- Union members, communities, and Congressmen became advocates

NG Loco Demo Program

Burlington Northern Railroad 1988-1995

(continued)

- Two SD40-2 locomotives with EMD 645 engines were converted to run on NG with low-pressure early-cycle kits from Energy Conversions, Inc. (ECI), These were the first diesel locomotives anywhere with electronically-controlled fuel injection; made it easy to change injection timing.
- The tender cars fed two locomotives simultaneously and had sufficient LNG for a complete round-trip from fueling station to coal mine to power plant or port and return.
- Tender cars had frame-braced trucks for stability.
- LNG tank insulation was tested at TTC.
- Locomotives were equipped with health-monitoring system and data radios for real-time on-board monitoring.

NG Loco Demo Program

Burlington Northern Railroad 1988-1995

(continued)

- Locomotives underwent 500 hours of stationary testing before over-the-road tests began.
- Engine ran on diesel fuel when idling and through notch 2; NG injection initiated at notch 3, and, by notch 8, 95% of the energy was provided by NG and 5% by diesel fuel.
- Locomotives were equipped with methane gas detectors; they would shut off the gas at the tender and on the loco, and the loco would automatically switch to diesel fuel.
- Hoses between tenders and locos had air-operated, spring-loaded-return safety shut-off valves.
- Project partner for tender cars and fueling station (at Staples, MN where LNG was trucked in) was Air Products & Chemicals, Inc.; BN spent about \$10 million on the project

NG Loco Demo Program

UP and BNSF in LA Basin 1993-2013



NG Loco Demo Program

UP and BNSF in LA Basin 1993-2013

- Four Morrison-Knudsen 1200G switcher locomotives equipped with Caterpillar 3516G spark-ignited gas engines; two leased to UP and two to ATSF, went into service in 1995
- Diesel version of Cat 3516 engine rated at 2000 HP; gas version at 1200 HP.
- LNG carried in belly tanks; gasified on-board for direct injection into cylinders; LNG was trucked in to fueling station.
- Program demonstrated reduced emissions in the LA Basin; locos retired after 20 years of service.
- Because they did not consume much fuel, there was an issue of boiling off and venting of methane.

NG Loco Demo Program

Union Pacific 1992-1995



NG Loco Demo Program

Union Pacific 1992-1995

(continued)

- UP undertook a program with GE and EMD to look into high-pressure (3000 psig) late-cycle injection of LNG into engine cylinders with pilot injection of diesel fuel
- Photo shows a GE C41-8W locomotive and a tender equipped with cryogenic pumps
- Limited stationary testing at the two locomotive builders (5 hours at GE), and the locomotives never entered revenue service
- GE's Chief Engineer: "We proved that NG locomotives won't work!"

NG Loco Demo Program

Brazil 2010- present



NG Loco Demo Program

Brazil 2010- present

(continued)

- Three GE Dash-9 locomotives with 7FDL16–EFI engines converted in 2010-2011 with ECI dual-fuel kits to inject NG into inlet air; NG replaces 50% of diesel fuel
- Engines derated from 4400 HP to 4000 HP.
- Operate on Vitoria-Minas Railroad (EFVM), in southeast Brazil – an iron ore heavy haul line
- Tender car in photo is a prototype; conventional cryogenic tank cars have since been built

NG Loco Demo Program

Canadian National 2012-present



- Uses the same technology as the BN NG locomotive demo program of 20 years earlier (i.e., ECI dual-fuel conversion kits, revised coolant cycle)
- Now in revenue service in Alberta

NG Loco Demo Programs

BNSF, CSX, NS, UP 2013-

- BNSF is “working with both GE and EMD on dual-fuel natural gas locomotives.”
- CSX is “studying the technology.”
- NS is “working with loco manufacturers and studying CNG-powered engines in addition to LNG.”
- UP is “working closely with loco and engine manufacturers, cryogenic fuel-tank suppliers and natural gas/LNG suppliers.”

That's all the information that is published!

Economics of Natural Gas vs. Diesel Fuel

Futures prices from the Wall Street Journal,
July 13, 2013, page B13:

- **Heating oil #2: \$3.03 per gallon**, or equivalent cost per unit of energy with natural gas at \$21.50 per million BTU
- **Natural gas: \$3.65 per million BTU**, or almost 1/6th the price of heating oil #2 per unit of energy (Note: this does not include the cost of liquefaction of natural gas)

Railroads consume about 4 billion gallons of diesel fuel annually. If 20% of that amount were displaced by natural gas, railroads would save about \$2 billion in fuel costs annually.

Summary

- The implementation of natural gas locomotives requires “systems thinking.”
- The economics of natural gas as a loco fuel are attractive now, but only on specific routes.
- Railways might mitigate the effects of future price fluctuations with long term NG contracts.
- The technology works.
- Education of railway workers, customers, and communities must take place.
- On BN, our train crews, union reps, locomotive maintainers, communities, and even Congressmen became advocates of natural gas.

Questions ?



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Early Natural Gas Bus in Chongqing, China



Supplemental Slides

Why are we discussing them?

Progressive Railroading, September 28, 2012

“CN to test natural gas-powered locomotives”

Wall Street Journal, March 6, 2013

“Railroad [BNSF] Tests Switch to Gas”

Financial Times, April 14, 2013

“US rail operators divided over LNG future”

Trains Magazine, June 2013

“Bigger than the switch from steam: Using natural gas as fuel means big up-front costs, but huge savings for railroads”

Topics

- Properties of natural gas (methane) and related hydrocarbons
- Liquefied natural gas (LNG) vs. compressed natural gas (CNG)
- Availability and use of natural gas in the US
- Economics of natural gas vs. diesel fuel
- How to haul LNG and CNG
- Engine issues
- Equipping locomotives – road units vs. switchers
- Fueling station issues
- Natural gas locomotive demonstration programs
- Natural gas buses
- Safety and perceptions of safety
- Environmental issues
- Order-of-magnitude costs for locomotives, tenders, and fueling stations
- Related concepts to avoid
- Summary

Properties of Natural Gas

- NG primarily consists of methane, CH₄
- Methane is an colorless, odorless, tasteless, non-toxic gas
- An odorant (mercaptan) is often added as a safety measure so it can be detected
- Methane is lighter than air at room temperature and standard pressure (1 atm); it disperses
- Methane is flammable only over a narrow range of concentrations (5 to 15%) in air; it won't burn if the mixture is too lean or too rich
- $\text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}$
- Boiling point of methane is -161° C
- Liquid methane does not burn

Properties of Related Hydrocarbons

- **Methane (CH_4)** is the simplest molecule in the alkane family, whose members have the formula: $\text{C}_n\text{H}_{2n+2}$
- Natural Gas Liquids (NGL) – a/k/a Liquefied Petroleum Gas (LPG) – consist of **ethane (C_2H_6)**, **propane (C_3H_8)**, and **butane (C_4H_{10})** and are derivatives of raw natural gas, extracted during gas refining; are liquid under pressure; at atm pressure are gases heavier than air and do not disperse.
- Gasoline is a mixture of alkanes from **pentane (C_5H_{12})** up to about **decane ($\text{C}_{10}\text{H}_{22}$)** .
- Kerosene contains alkanes from about $n=10$ to $n=16$.
- Alkanes with higher values of n are found in diesel fuel, fuel oil, petroleum jelly, paraffin wax, motor oils, and for the highest values of n , asphalt.

Liquefied Natural Gas (LNG) vs. Compressed Natural Gas (CNG) vs. Diesel

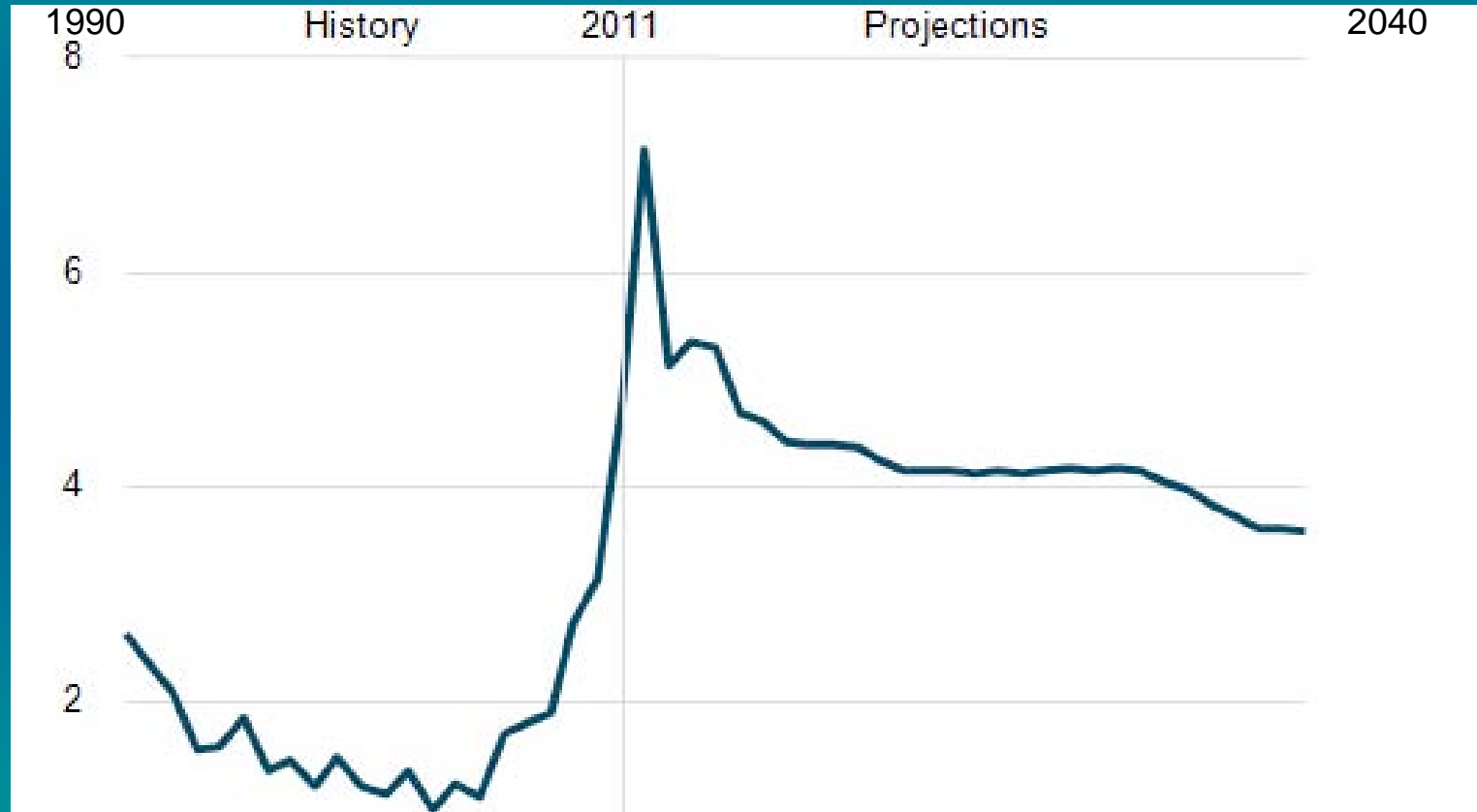
	CNG	LNG	Diesel
Energy content, BTU/gal	19,760	76,300	129,400
Storage-to-atm expansion ratio	160	649	1
Storage pressure, psig	2400	25-60	0

Availability and Use of Natural Gas in the US

- 200+ years supply of natural gas in the US
- 150,000 natural gas vehicles in the US and 5 million worldwide
- 50% of the households in the US use natural gas for heating and cooking
- In 2012, the US consumed approximately 25.46 trillion cubic feet (Tcf) of natural gas:
 - Electric power generation: 9.14 Tcf (36%)
 - Industrial: 7.10 Tcf (28%)
 - Residential: 4.18 Tcf (16%)
 - Commercial: 2.90 Tcf (11%)
 - Lease and plant fuel consumption: 1.39 Tcf (5%)
 - Pipeline and distribution: 0.71 Tcf (3%)
 - Vehicle fuel: 0.03 Tcf (<1%)

Economics of Natural Gas vs. Diesel Fuel

Ratio of Brent crude oil price to Henry Hub spot natural gas price per unit of energy



Source: US Energy Information Administration, *Annual Energy Outlook 2013*,
Market Trends – Natural Gas

http://www.eia.gov/forecasts/aeo/MT_naturalgas.cfm#natgas_prices

How to Haul LNG and CNG

➤ Tender Cars – preferred for road locomotives

- LNG – Typically 20,000 gallon tank car with center sill, cryogenic (i.e., heavily insulated); equivalent to 11,800 gal of diesel fuel. Two options for moving the NG to the locomotive:
 - On-board heat exchanger to gasify the NG to a pressure of 100 psig for transmission to the locomotive
 - Cryogenic pump to move LNG at 3000 psig to the locomotive
- CNG – Heavy duty flat car with center sill, carrying 90 ft³ steel cylinders; 17 cylinders would carry 1530 ft³ of CNG, equivalent to 2380 gal of diesel fuel.

➤ Belly tanks – preferred for switching locomotives

- Can carry LNG or CNG in lesser amounts

Order-of-Magnitude Costs for LNG Locomotives and Tenders

- LNG dual-fuel conversion kits cost on the order of \$500,000
- LNG tender cars cost on the order of \$1 million
- Therefore, approximate cost for two converted locomotives is \$2 million
- New locos with spark-ignited engines carry a premium of about \$1 million
- Costs need to be confirmed by talking with vendors; larger orders will reduce costs

Order-of-Magnitude Costs for LNG Fueling Stations

- LNG fueling stations with tanks to hold trucked-in LNG cost on the order of hundreds of thousands of dollars
- Combined LNG liquefaction plant and fueling station costs on the order of tens of millions of dollars.
- Energy to run LNG liquefaction plant can come from heavier hydrocarbons that boil off during the methane liquefaction process.
- Companies that build and operate LNG liquefaction plants could be willing to do that and charge railroads fully allocated cost of liquefying pipeline NG.
- Costs need to be confirmed by talking with vendors.

NG Loco Demo Program

Burlington Northern Railroad 1982-1987



NG Loco Demo Program

Burlington Northern Railroad 1982-1987

- This was a proof of concept program.
- EMD gas conversion kit (made for gas-field engines) was applied to an EMD 567 engine in an EMD GP-9 locomotive; involved addition of a cam shaft to actuate the NG injectors; a new cam shaft would be needed to change timing of injection.
- Engine was derated.
- A highway CNG trailer was mounted on a conventional flat car; fed one locomotive.
- FRA required the “fifth wheel” on the flat car be rigid, not collapsible.
- Success led to next program with larger locos, electronic fuel injection, and LNG tenders.

NG Loco Demo Program

Russia 1990-1994



- Lugansk locomotive had two-stroke cycle opposed-piston engine (à la Fairbanks Morse)
- Tender car had four LNG cylinders, electro-mechanical gas sensors; LNG gasified on-board
- No over-the-road testing

NG Loco Demo Program

Russia 1990-2002+



- Kolomna switcher locomotive had four-stroke cycle in-line 8 cylinder engine; dual-fuel
- CNG contained in belly tanks
- Planned for service in Moscow area

Natural Gas Busses



Natural Gas Busses

(continued)

- Many thousands of CNG busses are now in service in the US.
- CNG is carried in tanks on roofs under the metal shields. (China used to use rubber bladders on bus roofs to hold CNG.)
- Most of the busses are built by New Flyer Industries, Inc. of Winnipeg, Manitoba, and have Cummins Westport CNG spark-ignited engines.
- CNG busses are refueled daily or more frequently.

Safety of Natural Gas

- Natural gas is quite safe; we use it to cook our food and heat our homes.
- Methane is flammable only over a narrow range of concentrations (5 to 15%) in air if there is an ignition source; if unconstrained, it will burn; if in a constrained space, it will explode.
- There are no specific FRA safety regulations regarding the use of NG as a locomotive fuel.
- FRA requires that hazardous materials being hauled in commerce be placed 5 car lengths behind the loco; no such requirement exists for loco fuels.

Safety of Natural Gas

(continued)

- Nevertheless, FRA has control of all safety matters, and wants gas detectors on locos and tenders to detect leaks and valves to shut down the flow of NG if there is a leak.
- In 1990, BN Railroad contracted with Los Alamos National Laboratory for a “Safety Analysis of Alternative Locomotive Fuels”.
- As expected, the analysis showed that diesel fuel was the safest locomotive fuel, LPG (propane) the most hazardous, and LNG, CNG, and methanol fell between them.

Perceptions of Safety

- Most people have heard of houses that have exploded due to leaking natural gas.
- People confuse NG (methane) with LPG (a/k/a NGL – propane and butane).
- Memories persist of LNG from ruptured tank running into sewers in Cleveland in 1944, followed by fires and 150 deaths.
- To address adverse perceptions of safety of NG, education and training of train crews, maintenance shop personnel, fueling station staff, communities, and first responders is absolutely necessary.
- Probably best to not use NG locomotives on passenger trains.

Environmental Issues

- There is no sulfur in NG; no oxides of sulfur (SO_x) are produced when burning NG.
 - r Most of the sulfur has been removed for diesel fuel now being delivered to railroads.
- Heat of combustion is less with NG than with diesel fuel; therefore less oxides of nitrogen (NO_x) are produced.
- NG and diesel fuel are both hydrocarbons, so their combustion produces both CO and CO_2 ; the amount of both produced is very engine specific.
- Methane is a greenhouse gas; complete combustion is important and leakage must be prevented.

Related Concepts to Avoid

➤ Propane

- Heavier than air; explosive
- More expensive than LNG

➤ Turbine engines

- More expensive than diesel engines
- Not dual-fuel capable
- Use almost as much fuel when idling as at full power
- Not really suitable for railroad applications; like to run at constant speed and like cold inlet air

➤ Hydrogen

- Smallest molecule; requires precision “plumbing” on locomotive
- Unlike methane, it does not exist naturally on earth; requires more energy to produce it than can be obtained from it as a fuel